An Autoranging Scale Expander

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A scale expander for analog signals is described in which the output is presented in the form of an integer voltage (the suppressed voltage) and a voltage representing the remainder of the input signal. Choice of the range (magnitude of suppression) is rapid and automatic. The instrument can be used, as an interface module, with a very wide variety of analog data systems. A few illustrative applications are given. Advantages in instrument performance over presently available circuits are documented.

INTRODUCTION

An instrumental system for the measurement of analog data can be considered as consisting of (1) a source of analog data and (2) a data acquisition module; these will, for the sake of brevity, be referred to as source and receiver. The sensitivity of the system can be increased by inserting between source and receiver an interface which first amplifies the output of the source and then subtracts from it a value accurately known and of the proper magnitude to bring the signal delivered to the receiver within its range of operation.

For many instrumental systems, such a combination of scale expansion and zero suppression or zero offset would permit realization of the full measuring capability of the system. However, to our knowledge, use of this potentially powerful tool has been quite limited. This is probably due to limitations in currently available methods for choice of the amount of suppression and of the scale. Manual suppression (such as supplied in some commercial p_H meters) is in many cases inapplicable, as with frequently or rapidly changing signals and with instruments unattended during any part of the data collection period. Automatic selection of the proper suppression can, in a sense, be achieved by use of a separate receiver output for each desired range of the (expanded) scale. An example is a two pen recorder, with one pen for the range 0–1 V, and another for the range 1–2 V (cf. some models of the Cary[1] spectrophotometer). However, the number of receivers which can be used is generally severely limited and this limits correspondingly the number of ranges available.

In a recent paper[2] a circuit was described which provides truly automatic suppression to bring the output into the range of the recorder. This circuit was designed for recording geomagnetic data. We have, independently, and for other purposes, constructed a scale expander of different design which also provides automatic suppression. Our circuit is of wide applicability and possesses certain important advantages, among which are the following.

(1) The output data contain all the information in the input signal, in the form of an integer voltage and a voltage representing the remainder of the input. (2) The value of the input is easily calculated because the magnitude of each step of suppression is 1 V, and the total amount of suppression is presented as part of the output data. (3) No negative output signals need to be dealt with (for positive input signals). (4) Maximum utilization of the range of the receiver for the suppressed output is effected. (5) Negative input signals could be accommodated easily by addition of appropriate stages, without loss in efficiency of utilization of the range of the receiver. (6) Output precision is constant on all ranges. (7) The instrument has an over-all accuracy better than 0.1% and is relatively insensitive to temperature changes because components having high temperature coefficients are not used. (8) The total cost, exclusive of power supplies and packaging, is less than 50 dollars.

The circuit as described below expands the scale of the receiver fivefold. This is accomplished by four stages of suppression. Tenfold expansion could be achieved readily. For brevity, the instrument will be referred to as ARSPAN, standing for autoranging scale expander.

I. DESIGN

A. Principles

A block diagram of the instrument is shown in Fig. 1. The positive signal from the source, if not already in the 0–5 V range, is suitably amplified (not shown in diagram, because design details will depend on the characteristics of the source). A 0–5 V signal thus is the input to stage A,

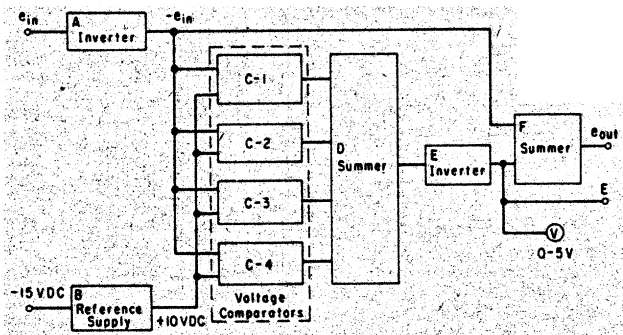


FIG. 1. Block diagram of autoranging scale expander (ARSPAN).

which serves to provide a fixed input impedance. The inverted signal is then brought to four voltage comparators (stages C1–C4), each of which has, as a second input, +10 V (provided by a stable supply, stage B). By suitable choice of the input resistors, the four comparators are set to trigger at (negative) input levels slightly greater (in absolute value) than 1, 2, 3, and 4 V, respectively. When the trigger level in a given comparator is exceeded (in the negative direction) its relay closes, making the corresponding input to the 4-port summer (stage D) +10 V. The 10 V signals are summed, reduced in magnitude by a factor of 10, and, incidentally, inverted. The reduced and inverted integer sum (0, −1, −2, −3, or −4 V) is inverted in stage E to a positive value E and in this form constitutes one of the inputs to the two port summer (stage F). The other input to the latter is the (amplified and) inverted source signal, $-e_{\mathrm{in}}$, from stage A. The nonintegral output of the summer, e_{out}, is therefore $e_{\mathrm{out}}=-(-e_{\mathrm{in}}+E)=e_{\mathrm{in}}-E$, the input voltage, less an integral number of volts. E is generally the largest integer less than e_{in}, so that e_{out} is between 0 and 1 V. (When the magnitude of e_{in} is in the small interval between an integral value and the trigger level above it, e_{out} is slightly greater than 1 V.)

There are thus two outputs from the ARSPAN, an integral output E, and a (generally) nonintegral output e_{out}. Together they contain all the information present in the input: $e_{\mathrm{in}}=E+e_{\mathrm{out}}$. E is read out on an inexpensive panel meter graduated in five steps of 1 V each. A 1 V receiver for e_{out}, together with the panel readout of E, therefore provides an expanded scale for measurement of the 0–5 V input e_{in}.

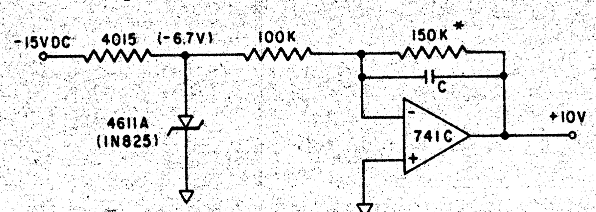


FIG. 2. Circuit diagram of reference supply (stage B).* 150 kΩ is the nominal value. The exact value is one obtained by component selection so as to provide an output of exactly 10 V

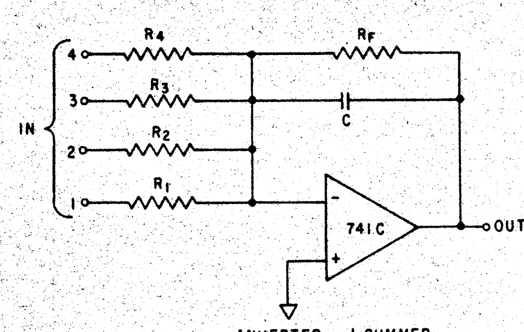
As with e_{out}, E can be presented in digital form by use of a simple code conversion. If recorded analog output is desired, a small auxiliary recorder, or a second pen on the recorder utilized for e_{out}, can be used.

B. Construction

Circuit diagrams for the various stages are given in Figs. 2–4. It is convenient and efficient to mount each stage on a separate circuit board, and to mount these, in turn, on a mother board, which also holds the ±15 V supply.

All critical resistance values R were obtained by placing two resistors, R_1 and R_2, in series. R_1 was chosen so that $R_1>0.97R$. After soldering one end of R_1 in place and allowing a few minutes for cooling, its resistance was measured, and a second component with a resistance value $R_2=R-R_1$ was soldered in series with it. The over-all resistance was then measured, to ensure that, within 0.03%, the desired value was obtained. All resistance measurements were made with a digital ohmmeter accurate to 100 ppm of full scale.

Any given voltage comparator will trigger at different levels for increasing and decreasing signals. The difference between the two levels, the hysteresis h, is set by adjustment of the variable hysteresis resistor R_H (Fig. 4). The mean trigger voltage (or null point[3]) T is selected by adjustment of the variable resistor R_2 (Fig. 4). T is independent of R_h, and can be chosen by setting $R_h=0$ and then adjusting R_2 until triggering occurs. An increasing signal triggers the comparator at $T+\frac{1}{2}h$, a decreasing signal at $T-\frac{1}{2}h$. If it is desired to avoid any negative output, $e_{\mathrm{out}}<0$, it is only necessary to make $T-\frac{1}{2}h$ slightly greater than the nearby integral voltage value N, which can be considered as the nominal trigger level. Thus, by setting $R_h=0$ and adjusting R_2 until $T=N+30$ mV, and then adjusting R_H until $h=30$ mV ($R_h\cong 100\,\Omega$), range changes



	INVERTER		SUMMER	
RESISTOR	A	E	D	F
R_1	100K	10K	100K	10K
R_2	Not Used	Not Used	100K	10K
R_3	Not Used	Not Used	100K	Not Used
R_4	Not Used	Not Used	100K	Not Used
R_F	100K	10K	10K	10K

FIG. 3. Circuit diagram of summers and inverters (stages A, D, E, and F).

will occur at $N+45$ mV for increasing signals, and $N+15$ mV for decreasing signals, where $N=1$, 2, 3, or 4 V.

Each of the operational amplifiers of stages A, D, E, and F has a capacitor C in parallel with the feedback resistor R_F, to assure stability and filtering, if necessary. If filtering is not necessary a nominal capacitance of 1 nF is sufficient.

II. APPLICATIONS

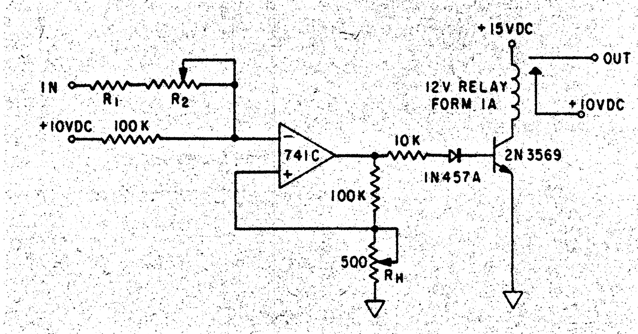
The ARSPAN should have application to virtually any analog data system where scale expansion is indicated, provided the actuate and deactuate times of the relays (ca. 500 μsec) and the slew rate of the operational amplifiers are taken into account. A few illustrations of how the system can be used will be given.

A. Analog Readout with Panel Meter

An inexpensive panel voltmeter with a range of 0–1.5 V, marked in steps of 0.02 V, was used. An uncertainty in the readings of 0.02 V will be assumed. The stable unknown signal to be measured e (when read directly on the voltmeter) read 0.78 V. The signal obtained after fivefold amplification served as e_{in}, the input to the ARSPAN. The integral output E from the ARSPAN was 3, and the nonintegral output e_{out} was 0.92 ($\pm$0.02). Therefore, $e_{in}=3.92\pm0.02$, and $e=e_{in}/5=0.784\pm0.004$. A comparison with the direct reading, 0.79 ± 0.02, illustrates the fivefold increase in sensitivity and precision achieved.

If the ARSPAN is to be used for a large number of such readings, it would be convenient to modify the outputs so that the unknown signal is calculated directly, $e=\frac{1}{10}E'+e'_{out}$ (where E' is an integer), division by 5 ($e=e_{in}/5$) being unnecessary. To accomplish this, the face of the panel meter formerly used for presenting E, in 1 V steps from 0–5 V, would be re-marked to read in five steps of 0.2 each, from 0–1. Likewise, the (second) panel meter reading e_{out} on a 0–1.5 V range would be re-marked to read e'_{out} on a 0–0.3 range, with the uncertainty correspondingly reduced to $(0.3/1.5)\times0.02=0.004$.

For the above example, values of $E'=6$ and $e'_{out}=0.184$ ($\pm$0.004) would then be obtained, giving $e=0.6+0.184\pm0.004=0.784\pm0.004$.



COMPARATOR	RESISTOR R1*	RESISTOR R2
C-1	9.5K	1K
C-2	19.1K	2K
C-3	28.7K	5K
C-4	38.3K	5K

FIG. 4. Circuit diagram of voltage comparators (stages C1, C2, C3, and C4).* Resistors are of the metal film type, tolerance 1%, temperature coefficient 50 ppm.

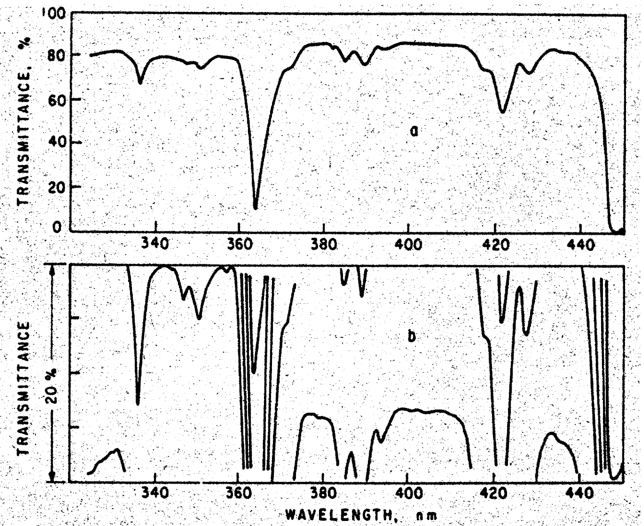


FIG. 5. Transmittance spectrum of holmium oxide. (a) Without ARSPAN module, and (b) with ARSPAN module. Pen markings made during range changes were, for the sake of clarity, omitted from the figure (b). For this spectrum the mean trigger level (T) for each comparator was set at the full scale value of the range, e.g., at 20% transmittance (1.000 V) for the first comparator.

B. Digital Readout

The same unknown signal as above, when measured directly on a $3\frac{1}{2}$ digit voltmeter, read $e=0.784$ V. The uncertainty here is 0.001. After fivefold amplification (to e_{in}) and passage through the ARSPAN, outputs $E=3$ and $e_{out}=0.918$ ($\pm$0.001) were obtained. Therefore, $e=e_{in}/5=(3.918\pm0.001)/5=0.7836\pm0.0002$. This again illustrates the fivefold increase in sensitivity and precision achieved by fivefold expansion.

C. Presentation of e_{out} on a Recorder

Figure 5 shows a transmittance spectrum of holmium oxide taken with a Beckman DBG spectrophotometer (a) without and (b) with the ARSPAN interface. For the unexpanded scan the recorder covers the range zero to 100% transmittance. In the expanded scan there are five ranges of 20% each.

To make possible presentation of spectrophotometric data in terms of absorbance instead of transmittance, a logarithmic converter is under construction. In conjunction with this converter the ARSPAN will permit direct acquisition of absorbance data covering the range 0–2 absorbance units in five steps of 0.4 each, with a readability of 0.001 absorbance unit.

III. DISCUSSION

In the examples presented it is to be noted that the range of the receiver (for e_{out}) can be fully utilized. The efficiency of utilization is determined by the hysteresis, i.e., the difference in the trigger levels for increasing and decreasing signals (see Sec. I). This can be varied at will, in the ARSPAN, by adjustment of the variable hysteresis resistor (Fig. 4, R_H). Hysteresis should be large enough to prevent a high frequency of range changes due to a signal hovering about a mean value near the trigger levels; it should be small enough not to diminish substantially the effective range of the receiver. A value of 100 Ω for R_h (Fig. 4) provides about 30 mV of hysteresis, corresponding to 3% of the 1 V receiver range.

Another advantage of the circuit presented is that the magnitude of each step of suppression is equal to the nominal range of the receiver. The desired datum is therefore an easily calculated sum. Thus in Fig. 5, where the recorder range was 20% transmittance, a value for e_{out} of 5.0% of full scale and for E of 3 V represents a transmittance of $3\times20+0.050\times20=60+1.00=61.00\%$.

In terms of voltage (for $e_{out}=5.0\%$ of full scale and $E=0$, 1, 2, 3, and 4 V, respectively) $e_{in}=0.050$, 1.050, 2.050, 3.050, and 4.050 V. This illustrates the fact that the precision of data obtained with the ARSPAN is constant, i.e., independent of the offset E. This was achieved by careful choice of all critical resistors to within 0.03% of the ideal value, as described above.

The present instrument provides fivefold scale expansion and has an over-all instrument accuracy better than 0.1%. Tenfold expansion, and higher accuracy, could be achieved simply by using additional comparators, with an appropriate increase in the number of inputs to the summer (stage D). More stringent control of components would then be necessary, as follows: (1) The reference supply (stage B) would have to be of higher stability with respect to time and temperature; (2) mercury wetted relays should be used, in place of reed relays; (3) wire wound resistors should be substituted for metal resistors; and (4) chopper stabilized amplifiers may have to be used.

[1] Mention of commercial names does not imply endorsement by the U. S. Department of Agriculture.

[2] D. Trigg, Rev. Sci. Instrum. **41**, 1298 (1970).

[3] Philbrick Nexus Research, "Applications Manual for Operational Amplifiers," Sec. II.41, p. 58; and Sec. III.79 (1968), p. 101.